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TD-02-006
02/19/2002

Peak field definition in HFDA magnet series

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Introduction

In order for superconducting accelerator magnet to operate at the maximum efficiency, the peak field point should belong to the coil straight section. It ensures the current-carrying capacity of a largest superconductor volume being exploited at its maximum, thus providing minimum coil volume (cost) for generation a given field strength within a given aperture. 3D optimization of the first model in HFDA series was described in [1]. The iron yoke length was set to 600 mm (±300 mm from the coil geometrical center) providing the peak field ratios (the peak field within coil ends with respect to the straight section) of 92 % in the return and 89 % in the lead ends.

Starting from HFDA02 model, a new coil end design has been implemented. Apart from that, shorter distances between iron yoke and coil ends, envisioned for the next models due to technological reasons, made it necessary to revise the peak field calculations.

Model description

New coil end design [2] has been implemented in the finite-element model. Coil (shoe to shoe) and iron yoke lengths have been chosen equal to 1000 mm and 600 mm, as in HFDA02/HFDA03 models. The yoke magnetic properties were described by BH curve measured for the relevant steel with saturation magnetization of 2.12 T. The finite-element model, calculated using OPERA3D/TOSCA code is presented in Figure 1.

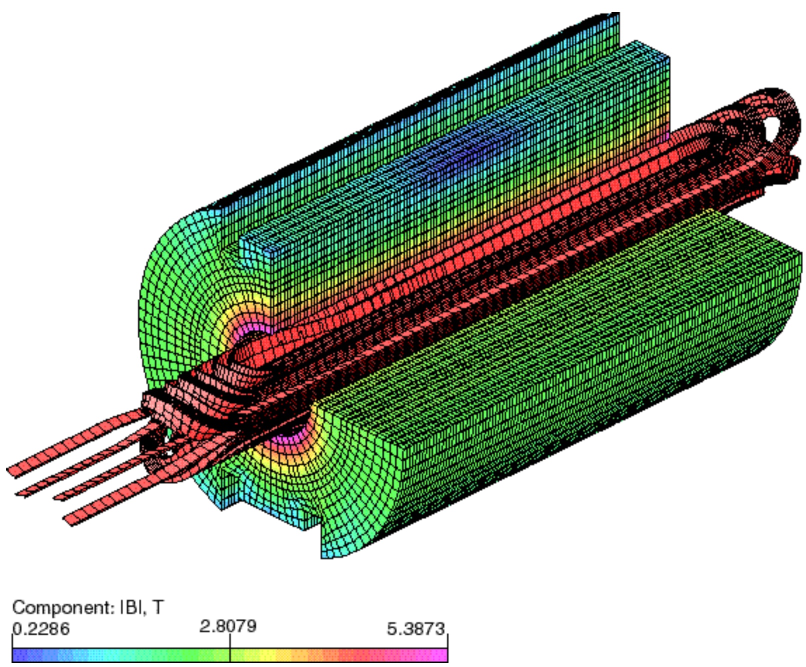

Figure 1. 3D finite-element model with flux density distribution in the iron at 10 T (one iron quadrant is removed for clarity).

Peak field ratio in HFDA02/HFDA03 models

Figure 2 shows the field distribution along the pole cable edge of the inner layer (where the field is maximum) from the pole piece centers of the lead to return end. In order to have possibility of independent manipulation of the coil and iron lengths, field contribution from these elements has been calculated separately. One can see peaks at both coil ends on the coil contribution curve, when the iron contribution has maximum (and nearly constant) value in the magnet body, decaying at the ends. Therefore, optimizing distances between coil and iron ends it is possible to adjust the peak field ratio from **86 %** (short yoke) to **106 %** (long yoke). In HFDA02/HFDA03 models, the peak field ratios happened to be the same for both ends and equal to 91 %.

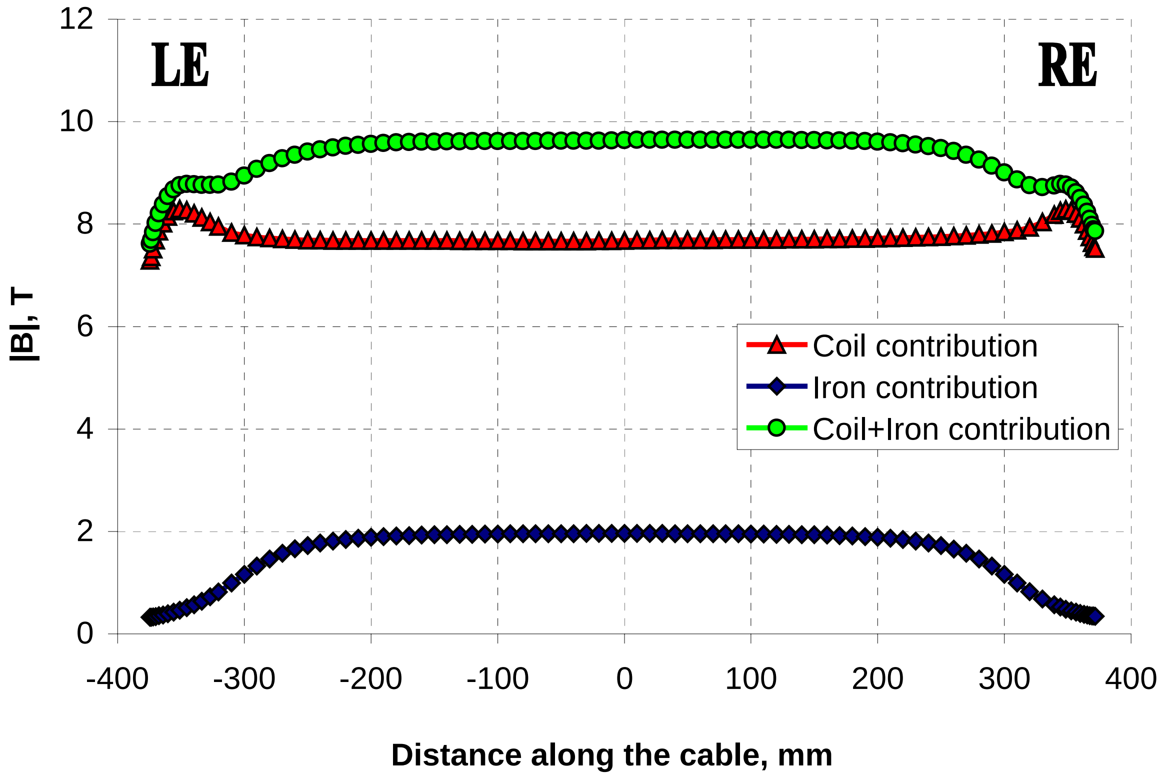

Figure 2. Peak field distribution in HFDA02 model at 16 kA.

Peak field ratio in the next models

The iron is highly saturated at quench field level, thus providing nearly constant contribution to the field. This feature has been used to avoid the extremely time consuming 3D simulations for every possible length of coil and iron yoke, envisioned for the next models. In order to simplify the results representation and avoid possibility of misunderstanding, it was necessary to set up a parameter, which will describe mutual position of coil and iron ends. Figure 3 shows the proposed convention, where L_{lead}, L_{return} represent distances between iron yoke end and the far-most point of the last spacer (before end shoe) in coil outer layer, as seen from the top. This parameter can easily be derived from the coil drawings, similar to [2] and will not turn to zero for any feasible design with the peak field ratio < 100 %.

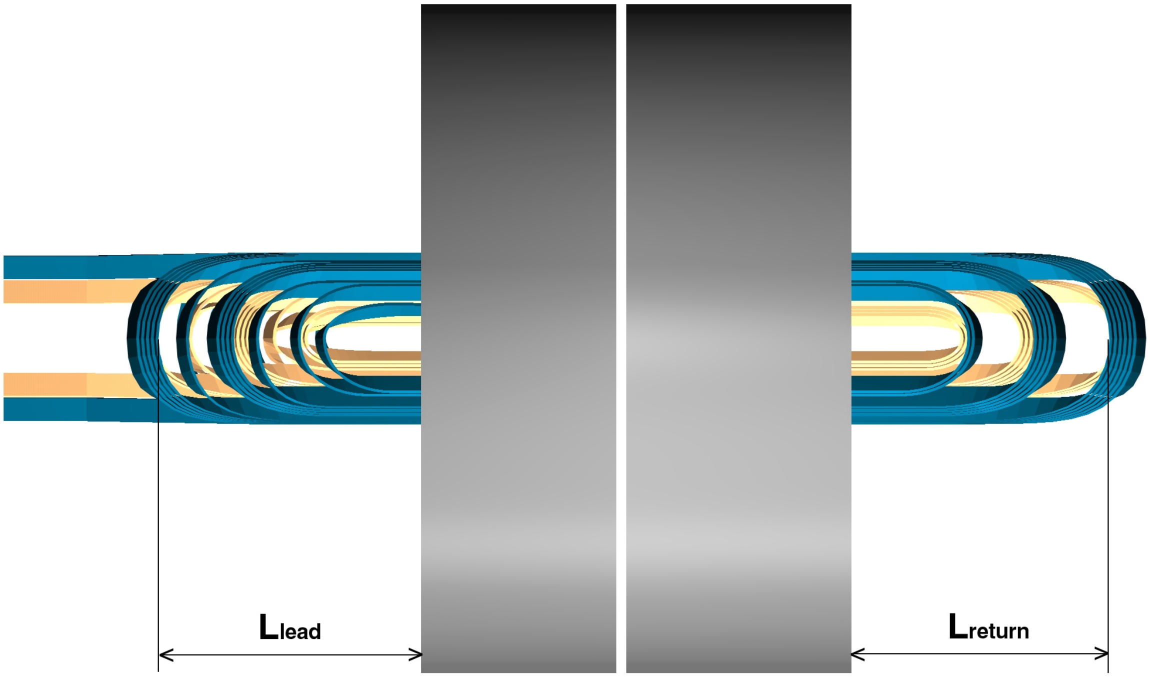

Figure 3. Convention for the coil and yoke arrangement.

The end distances, derived from the HFDA02 drawings were L_{lead} = 150.83 mm and L_{return} = 156.86 mm. It made possible scaling the iron yoke length (by extending the central part) and finding the peak field distributions for different $L_{lead} = L_{return} = L_{end}$, presented in Figure 3. The peak field ratios for the lead and return ends as functions of the L_{end} are shown in Figure 4. One can see that the peak field ratio goes above 100 % for the L_{lead} < **93 mm** and L_{return} < **99 mm**, which can be treated as ultimate boundaries for the coil end lengths.

The total number of stainless steel half-laminations (25 mm thick) for HFDA04 and HFDA05 magnets is 71 [3]. It means there would be 17 lamination layers per each magnet if to divide them equally, plus 3 unused half-laminations. Ordering of 1 additional half-lamination allows increasing the number of layers to 18 per magnet and makes use of all available laminations. According to HFDA04 drawing [4], there are 20 stainless-steel lamination layers and L_{lead} = 155.0 mm, L_{return} = 170.6 mm. In order to reduce the number of laminations, one has to replace several stainless steel layers with iron. Table 1 presents two possible cases of arranging stainless steel and iron laminations in each magnet.

Table 1. Arrangement of iron/stainless steel laminations.

Case #	Layers / magnet		End distances, mm		Peak field ratios, %	
	SS	Iron	L_{lead}	L_{return}	Lead	Return
1	17	24	130.0	120.6	93.9	96.1
2	18	23	130.0	145.6	93.9	92.5

There is unequally of peak field ratios within lead and return ends in both cases. In order to make them equal, adjustment of the coil to yoke longitudinal position is required. Table 2 summarizes the necessary adjustments in both cases.

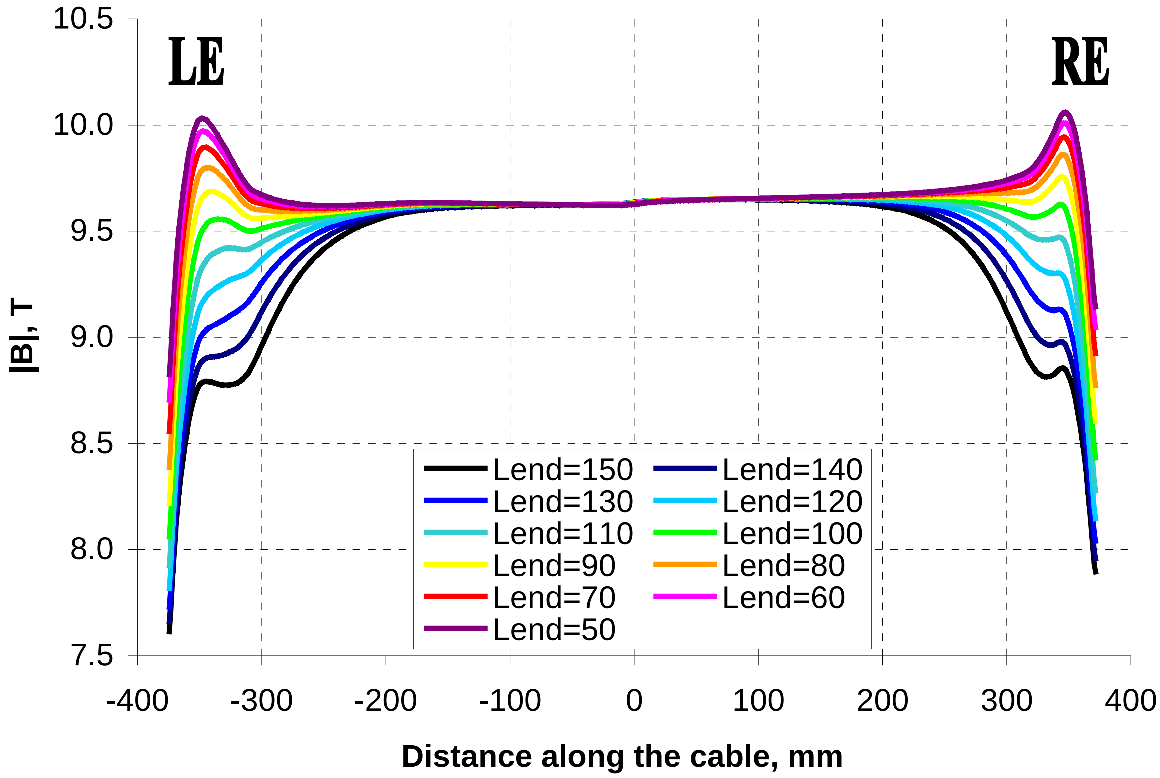

Figure 3. Peak field distribution for different end lengths at 16 kA.

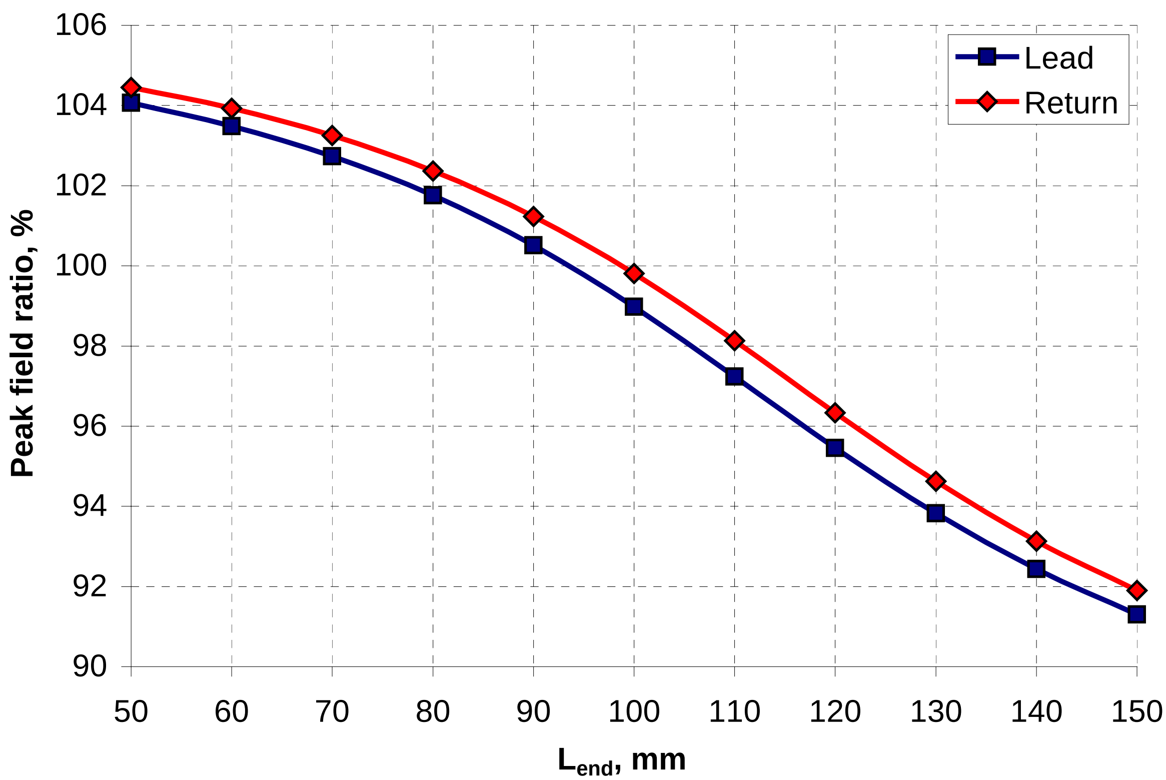

Figure 4. Peak field ratio as function of the coil end lengths.

Table 2. Adjustment of the coil to yoke position.

Case #	Yoke half-length*, mm		End distances, mm		Peak field ratios, %	
	Lead	Return	L_{lead}	L_{return}	Lead	Return
1	370.2	229.8	122.8	127.8	95.0	95.0
2	357.8	217.2	135.2	140.4	93.1	93.1

References:

1. G. Ambrosio, N. Andreev, S. Caspi, K. Chow, V.V. Kashikhin, I. Terechkine, M. Wake, S. Yadav, R. Yamada, A.V. Zlobin, Magnetic design of the Fermilab 11 T Nb_3Sn short dipole model, MT-16, IEEE Transactions on Applied Superconductivity, v. 10, No. 1, March 2000, pp.322-325.
2. FNAL TD drawings #5520-MD-376171 and #5520-MD-376175.
3. Communication with D. Chichili.
4. FNAL TD drawings #5520-ME-411183 and #5520-ME-411237.

* Distance between center of the coil straight section (outer layer piece) and corresponding iron yoke end. Given for reference only and valid for coil in accordance with [4]. Control of L_{end}, L_{rerurn} is preferable.